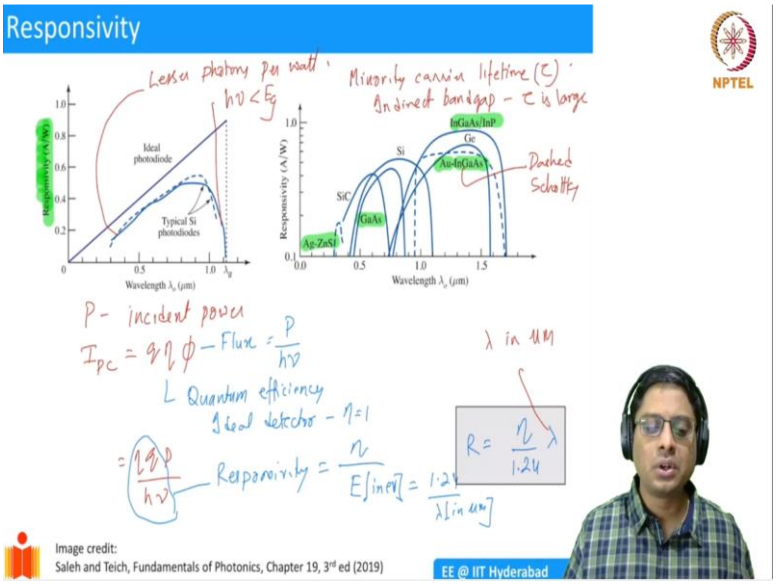
Introduction to Semiconductor Devices
Dr Naresh Kumar Emani
Department of Electrical Engineering
Indian Institute of Technology – Hyderabad

Lecture - 11.6

Photodetector Metrics.

Welcome back. So, in this video I would like to discuss a few metrics that are used to evaluate photo detector. So, this will not be exhaustive this is the first level. So, we will just introduce some of the responsivity which is one of the most important metric and then we will just mention other things. So, of course you know there are a whole lot of things that are required for practical device design.

(Refer Slide Time: 00:41)



Responsivity

Lesser photons per watt

$h\nu < E_g$

Minority carrier lifetime (τ)

Indirect bandgap – τ is large

Dashed Schottky

P - incident power

$I_{pc} = q\eta\phi$ – Flux $= \frac{P}{h\nu}$

L Quantum efficiency

Ideal detector – $\eta = 1$

$= \frac{\eta q P}{h\nu}$ — Responsivity $= \frac{\eta}{E[\text{in eV}]} = \frac{1.24}{\lambda[\text{in um}]}$

λ in um

$R = \frac{\eta}{1.24}\lambda$

Image credit:
Saleh and Teich, Fundamentals of Photonics, Chapter 19, 3rd ed (2019)

The first thing we will talk about is responsivity. So, this is a very important metric, because it quantifies how many electrons are produced? When you have a certain amount of you know how much current is produced by detector per unit power? Your essentially your input is optical power which is let us say P you know power incident power like let me call it as incident power 1 milli watt, 1 micro watt whatever incident power.

How much is current that is produced? We would like to estimate that and that can be captured by what is known as responsivity. So, I will say, current photocurrent is going to be equal to what? Well, if you have an incident power that is going to have some definite flux of photons, how many photons are there per second? We can compute that we have done it in the past. So that I will call it as 5 which is basically flux of photons.

And then not all of them will produce electrons. So, to capture that we will introduce a parameter which we call us quantum efficiency η. I will just talk about it in a moment. And then of course, the charge. So what are these parameters? Well, ϕ is the flux of photons, flux density you could call it. How much is it? This is going to be if you have flux power of P, we have seen that the number of photons that are produced per second per centimeter square is going to be hγ.

There is the energy of the photon, of course you have to put a Q there. Because, if it is an E V of course, you have to put a Q otherwise $\frac{P}{h\gamma}$ will be the flux, the number of photons that are produced per second. So, η is the quantum efficiency. Essentially how many electrons is producing per photon? And ideal detector, this is going to be η equal to 1.

If it is not ideal, we will see that it is never going to be ideal. It is going to be slightly lower quantum efficiency but we would like it to be as close to 1 as possible and the last one is charge. So, you can actually you know, rewrite this. So, this will be $\frac{qP}{h\gamma}$. And so, the current versus power the responsivity, we are defining as the amount of current that is produced per watt.

So, the way we are defining is in the ampere per watt. So that can be captured by this expression here, this term is called as responsivity. So, what is this? Oh well rather I forgot theta. So, this is going to be $\frac{\eta qP}{h\gamma}$. Well, hγ is energy of the photon divided by Q is basically the energy of the photon in the eV units. So, this will be equal to η by energy in eV.

eV times power, our responsivity is going to be simply η by this one. And we know that this guy is going to be equal to 1.24 divided by lambda in micrometers. So responsivity now, R is going to be equal to theta by 1.24 times lambda in micrometers. This is the responsivity for ideal photo detector. So, if you have lambda equal to 1.24 microns and this is basically this is lambda in micrometers.

$$Responsivity = \frac{\eta}{E[in\ eV]} = \frac{\eta}{1.24}\lambda[in\ \mu m]$$

So, if lambda is 1.24 responsivity is going to be 1. And that is what is shown on the graph here. So, as you have ideal photo detector, responsivity should go up to 1.24. If your lambda is larger of course you know to show something but what happens is if you are above the band gap you are not going to get any responsivity that is why it is quickly drops here.

And then for the lower wavelengths, you are going to have smaller current that is smaller responsivity. But this is the ideal case, if you have a realistic case the responsivity is going to be something like this. So, if your photon is actually having longer wavelength that means the energy is less than the band gap and it cannot produce any electron hole pairs. So, on the longer wavelength, it has to drop.

On the shorter wavelength, I mean if your energy is very, very large, per watt of photon per watt of optical energy we will have lesser number of photons. So, lesser number of electrons. So, here lesser photons per watt. As you because power is you know what a unit power and as you go to lower and lower rate, hence, the energy of the photon is larger.

So, the number of photons per watt is going to be less and that is where the responsivity drops. Because, we are essentially capturing responsivity in terms of number of electrons per watt. So, I mean indirectly it is going to be proportional to the number of photons. So, on the higher wavelength side, this is basically dropped because energy is sorry, hγ is less than Eg, so, responsivity 0 there.

So, this is the typical curve you will see. Well this is for silicon, it turns out that you can have various materials because the beginning of the photo detector discussion I said that we would like to have detectors in various wavelength ranges. For silicon, you can go up to 1.1 microns in the longer wavelength range but you cannot do better than that. So, if you want to have a longer wavelength detection. We need to use for example, germanium.

Germanium has a band gap of point 8 eV. That means it can detect up to you know 1.5 microns or so. So, that is why you see that the curve here. This is basically germanium which is having a photo detection of up to 1.5 microns and you have slightly better responsivity. And silicon has this responsivity in various materials. Now, you see that there are a couple of other materials here. We will talk about it in the next week.

These are basically 3 5 materials, the other 3 5 materials, we will talk about it. So, gallium arsenide, indium arsenide and so on. So, you might be wondering, you know, definitely some of you must be wondering that we said that silicon and germanium the indirect band gap materials and they are not very efficient interacting with light. Then how are you using them as photo detectors?

It sounds counterintuitive but you know, it is not the reason is for photo detection purposes, what we care is? You know how many electrons are able to collect. And one of the key parameters that influences that is a minority carrier lifetime. We have already seen that, you know, τ_p or τ_n minority carrier lifetime plays a crucial role minority carrier , minority carrier lifetime plays a crucial role for detection photo detection process.

What is that? Well, you are generating electron hole pairs and you do not want them to recombine. So, since we said that indirect band gap semiconductors are not good at the interaction of photons and electrons is not very efficient there. So, indirect band gap semiconductors, indirect band gap materials τ is large, relatively not τ is smaller for direct band gap materials.

That means, if you generate it is very efficient to generate electron hole pairs, but it is also efficient to recombine them. That is why τ is smaller for direct band gap semiconductors. Whereas indirect band gap semiconductors it can go up to even in 10 power minus 6 microseconds **scale** τ is large. And because τ is large, we can build the device in such a way that before it recombines we try to collect the electron.

τ is essentially capturing how many you know? How much time is there before electrons recap an electron hole electron and hole recombine effectively? So, before that recombination happens, we try to collect them in external circuit. And that is why even though silicon and germanium are not really that efficient materials for interacting with light.

We just increase the width of the material so that we collect more photons per unit length. Definitely direct band gap materials will absorb many more photons. But, we can overcome that by increasing the width of the material and then collecting the electron hole pairs. So that is my silicon even silicon solar cells you know, I started the discussion by saying that silicon is not a good material for optical electronic applications.

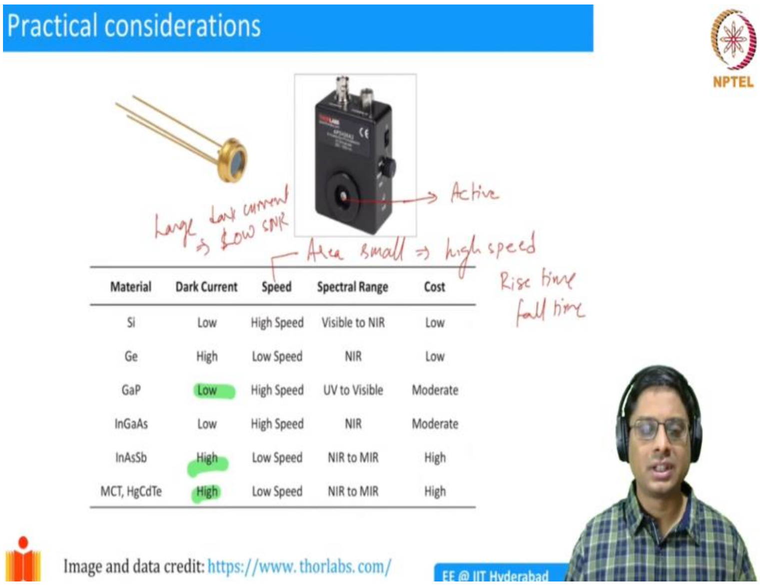
But then I showed you silicon solar cells. But the same reason, you know silicon also you can collect these electron hole pairs efficiently. That is why silicon solar cells behaves reasonably well. I mean, if you build a gallium arsenide base solar that is even better of course, you know, we do that, it has much better efficiencies, but it is expensive. So, for silicon is cheap so, we try to use silicon solar cells.

Similarly, you can make photo detectors out of silicon and germanium and they still work. So, responsively is one of the metrics that is very important. And you saw that you know, the responsivity of various detectors you know can be changed because each material has a different band gap and based on that you can have different amounts of responsivity. I mean, we can use PN junctions; we can also use schottky junctions.

You know for example here, what is shown is the Schottky junction. Now, in this case, silver and zinc sulphide junction can have responsivity even in the very small wavelength range and gold and indium gallium arsenide can have responsivity in the larger wavelength range. So, these are basically Schottky junctions now. These dashed curves now dashed Schottky junction even there you have a depletion region.

So, because of that you can use it for photo detector purposes and they have some advantages. So, there are a whole lot of materials that are available for us to choose from and how do we choose which photo detection to use? Well, it depends on of few parameters.

(Refer Slide Time: 11:42)



Practical considerations

Material	Dark Current	Speed	Spectral Range	Cost
Si	Low	High Speed	Visible to NIR	Low
Ge	High	Low Speed	NIR	Low
GaP	Low	High Speed	UV to Visible	Moderate
InGaAs	Low	High Speed	NIR	Moderate
InAsSb	High	Low Speed	NIR to MIR	High
MCT, HgCdTe	High	Low Speed	NIR to MIR	High

Image and data credit: https://www.thorlabs.com/

This is just a small short summary. It is by no means exhaustive, there are many more parameters that need to be considered but for the purposes of an introductory course. I thought I will just mention these. So, the images that you see on this slide are some images of practical photo detectors that are taken from the website thorlabs. Thorlabs is one of the suppliers of these things, prominent suppliers of various opto-electronic components and opto-mechanical components.

So, here what you are seeing is basically a PD of certain specifications. This specification is the written on the detector itself. And this is again a photodiode, a simple photodiode I showed you the schematic in the previous video. So, this is how practically it look like there are some leads that are coming out. You connect it to external circuit and you shine light on this guy here in the window and it will collect you know, it will generate current that is it quite small.

It looks like a BJT or something you know in the previous you can use them in the labs. Well I mean this is just 2 detectors. There are a lot lot more detectors. How do we choose from that? So, mainly there are 3 technical considerations that are important to us, one of them is the spectral range. So, we cannot use every detector in every spectral range for example silicon I can you know go from visible to near infrared.

I cannot really do better than that. So, this is going to be having better responsivity in this range. Whereas germanium is going to have better responsivity the near infrared. Near infrared is 1.5 micrometer and this is a very important spectral range for technology. Because, if you have optical fibers all of them are actually communicating at 1.5 micrometer 1.55 micrometer wavelength all the fibers every segment.

You have internet in your home. The fiber is actually having 1.55 microns and how are you connecting the optical signal into the electrical signal which is coming into a computer? Well, you need a photo detector there. And gallium phosphide in the UV you can reach similarly you know you have some other materials which are you know, indium aluminum antimonite and things like that which can work even into the mid-infrared.

For example, you want to detect you know temperature of a furnace, high temperature furnace 1500 Kelvin. You need some detecting in the mid-infrared range. If you want to detect human bodies, you know thermal imaging of human bodies. You know for example, nowadays you know, we have the pandemic. So, if you go into an airport they might want to screen you know for temperature but they cannot you know screen everybody with for temperature with a thermometer.

So, what they do is? They have this thermal imager installed. So when you have a person just going in front of it, if the person has a temperature the thermal imager will show you that will flag the person then they will stop him and then ask him a few questions. So that is how you can quickly screen. For example in airports, railway stations, you can have thermal imagers, which will work in the long wavelength IR and I am not even discussing those things here.

And there is a pretty expensive section. So, the spectral range or which the detector operates is an important parameter. Another important parameter is how fast it can operate? Some of them are high speed. Now for example silicon or you know, this 3 5 semiconductors this can be high speed sometimes. And one of the parameters that influences the speed is the area of the photo detector.

You know area small implies high speed. So that means, your collection area you know, for example, this guy here, I mean if you look at. If you go to thorlabs website and search for photo detectors, you will see a whole collection of detectors and you can analyze, you will start seeing that this area that is here, active area. If it is small then the photo detectors speed will be larger.

So and also, of course, you know the mobility of the carriers and all play a role. So there are various options that are available here. You can choose, you know, it is just you know, quantified as high speed, low speed. But in principle what you will look for is the rise time and the fall time. If your detector has nanoseconds of rise time, it is normal, it is going to be cheap.

But if you want a detector with pico seconds of rise time, that is going to be much more expensive. The reason is, let us say in a communication, you do not want to operate it, you now, megahertz, you want to operate it gigahertz, hundreds of gigahertz. As fast as possible, you want to switch them, you want to switch you know 0 and 1 you know switch on light, switch off light and measure that.

You know, pulsing for that you need a very high speed detector. For that you will want you know, Pico seconds hundreds of Pico seconds at least. So, if you want high speed then it is going to be expensive. Of course, that is like one of the parameters is cost, which you know I just how much is moderate? How much is low? How much is high? It depends you know, when you are when I was a student, I would say that even 100 dollars is expensive nowadays 10000 dollars is expensive.

So it depends on you what you are exposed to. And the last parameter is dark current. I have already alluded to that in the previous discussions. So. if you have a large band gap, you are going to have smaller dark current that is where gallium phosphide for example has 2 eV band gap and so it has low dark current. But if you go to MCT and these things indium antimonide, indium arsenic antimonide they have low band gap.

They can have high dark current. So, if what happens if you have high dark current? Well, large dark current implies low SNR. So, and what is the amount of limits of detectivity? How small can you detect and things like that in terms of noise equivalent power you know, if you increase your optical power, it is going to have more noise.

So, there is something called as noise equivalent power. You can calculate a whole range of parameters and you can choose which detectors to use based on those parameters. So, I hope I have given you a glimpse of photo detectors with these lectures. So, I will stop my discussion here. So far, in this week, we have discussed photo detectors, essentially devices that can connect photo detectors and solar cells.

Essentially devices which are converting light to electricity. So, this is one class of optoelectronic devices. In the next week, I want to talk about the opposite process. I want to generate photons from electricity. So, those are devices like LEDs, lasers and so on. And even displays, CCD displays. Sorry, charge checkable display will actually measure, well, you have displays also which are going to emit light.

So, we want to discuss light emitting devices in the next week of the course. And with that, I will close the discussion of the semiconductor devices. So, take your time, go back and look at the videos and if something is unclear, we will have a discussion one to one, you know we will have certain time slot that will be announced.

So you are welcome to you know approach me and we can discuss it further. So thank you very much. I will see you next week. Bye.